SXI-M RECALIBRATION ANALYSIS REPORT
POINT-SPREAD FUNCTION

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1. Purpose

This report addresses the SXI-M point-spread function (PSF) analysis, including both on-axis and off-axis performance. In addition, it touches upon issues related to background subtraction, which differ in certain respects from that covered in other portions of the recalibration analysis.

The PSF of an optical system is a measure of its ability to concentrate at the focal plane all the light from an infinitely sharp point source located far enough from the instrument that there are no parallax effects. Optical systems spread the image of a point source, so that some of the energy appears at angular distances away from the center of the point image. The distribution of intensity, I, as a function of distance, r, from the center of the point-source constitutes the PSF. (The function $I(r)$ is commonly normalized to I at the image center.) All optical components – mirror, filters, detector, etc. – contribute to the spread of the point-source as measured at the focal plane. For an X-ray system like SXI, this includes the figure of the mirror surface (and any associated micro-roughness), molecular and particulate contaminants, and all the elements of the detector.

Accurate knowledge of the PSF serves at least three main operational purposes:

1) The spreading of energy from localized bright sources tends to soften their boundaries, resulting in an image with a fuzzy appearance. Such features can be sharpened in routine post-processing, provided the PSF is known with sufficient accuracy.
2) Intense bright sources, like X-class flares, can overexpose the image by factors of $10^5 - 10^6$ in the worst cases. Thus portions of the CCD far from the flare site may pick up 10s or more DN, leading to a wide-spread fogging of the solar image. It is possible to remove some of this fogging with a well-defined PSF.
3) Physical interpretation of solar sources depends upon estimates of peak and total fluxes of solar sources, which requires an accurate PSF.

In addition to these operational applications, the derived PSF parameters can be related directly to SXI imaging specifications. That is, they also provide independent measures of the instrument sensitivity, focal properties, and filter transmissions, which were estimated by direct counting methods in the other recalibration studies (G. D. Berthiaume, "GOES-M SXI Calibration Report," Project Report NOAA-23, MIT/LL, 1998; J. M. Davis, "SXI Recalibration Report: Effective Area Measurements," MSFC memo ES82(98-064), July 14, 1998).

2. Approach

The PSF is measured by observing a point source of known intensity and angular size in the XRCF and analyzing the resultant spread of the signal across the CCD face.

Because of pixelation and noise effects in any particular image, it is necessary to add the information from many images to obtain sufficient statistical accuracy in the PSF.

In general, the X-ray PSF distribution will be bell-shaped, like a gaussian, but significant energy may be scattered to relatively large angles from image center. For SXI, the scattering is particularly pronounced at the shortest wavelengths. Fig. 1 shows a set of four individual point source images, at the wavelengths indicated. The entire CCD face is included in the display, and the grey scale has been adjusted so that the lowest DN values are enhanced. (The center of the image is thus saturated.) In this way, it is possible to view individual scattered photons far from image center to gain an impression of their distribution. At the shortest wavelengths many individual hits can be seen all across the CCD face. For this reason, it is necessary to measure the PSF to large distances (many 100's of arcsec) from the image center.

The concentration of the energy toward the core of the point-source image is determined in part by the mirror and in part by the detector. From slit scan tests run on the mirror alone and from detector resolution tests, it is clear that the width of the core of the image is dominated by the detector response, whereas the spread of energy to the wings of the image is regulated by the mirror. The response of the detector is a function mainly of the MCP voltage (and to a lesser extent wavelength), whereas that of the mirror is wavelength-dependent. The net instrument response then depends upon both MCP voltage and the source wavelength spectrum.

No correction is made for finite XRCF source size in this PSF analysis, since the angular diameter of the source ($\sim$ 0.2arcsec) is many times smaller than either the SXI pixel width or the measured spread of the point images at the detector.

3. Summary of Previous Analyses

Concerns about the absolute calibration of the SXI system and its overall sensitivity prompted the recent XRCF tests. Even if there were a problem with the sensitivity calibration, estimates of the PSF gained from the Feb 97 tests would not necessarily be invalid, since the PSF is a relative, as opposed to absolute, measurement. Only in the case where scattered light in the facility setup somehow makes it down to the focal plane would the PSF results be contaminated. This is not impossible, but it appears unlikely.

From the standpoint of PSF analysis, however, the primary shortcoming of the Feb 97 tests is that too few of any one kind of image (MCP voltage, exposure time, wavelength) were taken to permit adequate determination of the PSF. In addition, a reliable PSF provides a key corroboration of the sensitivity analysis, since the total DN in a given point-source image determined by direct counting methods should be consistent with that inferred from the PSF.

The most homogeneous set of images taken in that test was the filter series run 97/02/03. No more than 6 images of any one kind were taken, resulting in high residual noise levels. The PSF could not be traced out much beyond 50-70 arcsec with any degree of confidence (10^{-3} level in terms of signal). Examples of $I(r)$ from composited C and Al images are shown in Fig. 2. These images were taken at high voltage (910V) to provide the maximum exposure in the wings of the distribution. It is evident that the noise background is reached inside 100 arcsec. Thus the behavior in the far wings, most susceptible to fogging due to intense solar flares, could not be established and the statistical uncertainty in the core parameters were uncomfortably high.

4. Data Sets

It is necessary to determine the PSF over a range of wavelengths, MCP voltage settings, and field angles (on- and off-axis). However, practical considerations limited the imagery that could be taken. A strategy was therefore evolved to sample with a reasonable number of images key elements of the parameter domain, then take advantage of systematic functional relations in optical properties to fill in the gaps in the coverage. For instance, the width of the core of the image should be dominated by the detector response and vary with voltage, but the variation should be the same at Al and C. Conversely, scattering in the far wings of the image should be determined by the mirror figure, and should not be sensitive to the voltage. Hence, given sufficient knowledge of the PSF at the Al and C wavelengths, supplemented with additional imagery (of lower statistical weight) at intermediate wavelengths, MCP voltages, and field angles and with theoretical expectations of component responses, it should be possible to derive a reasonable functional description of SXI optical and photometric properties.

SXI system requirements were stated in terms of performance at two wavelengths, the 8.33Å Al K-α line and the 44.7Å C K-α line, and SXI detector response (DN/photon, as a function of MCP voltage) was measured only at these two wavelengths. Hence, although XRCF sources at intermediate wavelengths (9.89Å Mg K-α and 13.3Å Cu Lyman-α) were available and utilized during the recalibration tests, the primary PSF imagery was done at the Al and C wavelengths. Accurate measurement of the scattering in the wings at the Al wavelength is needed mainly to allay the effects of fogging of images from flares, whereas the PSF at the C wavelength is important for imagery covering a broad range of coronal structures, which emit predominantly at longer wavelengths.

PRIMARY DATA SETS FIGURING IN THE PSF ANALYSIS:

1) <u>873V field-angle images, Al and C sources.</u> This image series is used to determine the PSF out to large distances from the point image center and how it varies across the field of view. Due to time constraints and because the imaging properties of the instrument are presumed to be nearly symmetric about the SXI optical axis, the series was limited to angular offsets in just one direction (E-W, in the CCD operational orientation.) For this test, The SXI instrument was first aligned so that the point-source image would fall near the middle of the CCD array, and a series of 45 images was taken. The instrument was then slewed successively in pitch, with the point-source image being offset negative 6, 10, 14, and 18 arcmin from the nominal CCD center. (Negative pitch is opposite to the direction of charge advance in the CCD, or toward the top of the image as depicted in this report.) Again, 45 images were taken at each setting. The entire process was repeated on another occasion, so that approximately 90 images were collected at

each field angle. (A few images were eliminated due to saturation and various other flaws.) Due to an offset in the setup, the actual centers of the "on-axis" point-images fall approximately 2 arcmin farther from the CCD center than the setting value. Thus the "on-axis" images really refer to a position about 2 arcmin from CCD center, and the nominal -18 arcmin images are situated at about -20 arcmin, very near the edge of the field of view.

2) <u>On-axis C images taken over a range of MCP voltages.</u> Detector resolution tests demonstrate that the detector PSF varies measurably with voltage. Low XRCF source intensities and SXI throughput sensitivities limited the PSF imagery that could be obtained at short wavelengths, so that even at the longest possible integration time (65sec) full-well images could not be taken below about 870V at the 8.33Å Al wavelength. This is unfortunate, since the core of the point-source image is dominated by the detector PSF and dynamic response considerations militate SXI operating voltages in the range of 700-800V. However, because the detector PSF should be independent of wavelength, it suffices to measure the variation at the 44.7Å C wavelength, where the higher XRCF source strength allows for full-well exposures to much lower voltages. Lengthy series of images were taken at 873V, 828V, 747V, and 699V settings.

Additional information on the PSF as a function of field angle, wavelength, and MCP voltage can be extracted from other image series, and the analysis developed for the primary PSF study can be applied to these other data sets to measure additional aspects of the SXI optical performance. The main limitation is that there are far fewer images of any one kind, and thus the statistical accuracy is lower than for the primary PSF series. Also, not all these images were full-well exposed.

SECONDARY DATA SETS FIGURING IN THE PSF ANALYSIS:

3) <u>Fine pixel-scan analysis, 747V C source.</u> The fine scan test is intended to establish how strongly the PSF and the total DN collected depend upon just where in the pixel pattern the centroid of the point-source image falls. For this test, images were taken at a series of centroid locations finely separated in the x-direction, extending across several pixels near the CCD center. The horizontal scan was subsequently repeated with the image centroid offset half a pixel in the vertical direction. The first 24 images in the series were eliminated due to improper pointing offsets, leaving 156 useful images. All images were taken the same day.

4) <u>Focus map, 873V C source.</u> Two separate sets of 828V C images were taken to supplement the primary PSF off-axis series. In the first, four images were taken at a range of offset positions in a "+" pattern about CCD center. Four images at each of the extreme corners of the CCD were also recorded. A few days later, a second set of 10 images at each position, in the same pattern (except the corners), was repeated.

5) <u>Sensitivity series, SLF voltages, all sources.</u> These were the primary data sets for determining the SXI sensitivity in the XRCF recalibration tests. For each of the four sources, a set of images was taken at the three voltages used in the earlier

SLF tests, 910V, 840V, 750V. At each voltage setting, four images each at three different integration times were recorded. Although each set was completed in about an hour (minimizing any change in source or thermal conditions), each set was taken on a different day. The Mg set was later repeated with a source filter in place to suppress off-band emissions, and only this latter set was used in this analysis.

6) Filter set, all sources. These were taken to verify the values for the SXI filter transmissions determined in component tests and from manufacturer specifications. For each source, nominally 5 on-axis images were taken through each filter, with the integration time being increased for the densest filters to provide sufficient exposure. The Al and C imagery was run at 873V, the Mg and Cu at 910V. This is a relative measurement, as the important quantity is the total DN in the point image as compared with the same exposure in the "open" position (no filter).

7) Blooming set, 910V C source. A short series of images were intentionally overexposed to study the effects of image blooming, including detector saturation. At the long 65-sec integration time, the central pixel was overloaded by a factor of approximately 10. These few images are key to the analysis of the "halo" effect in the images.

Log files identifying the specific images analyzed in each data set are to be found in Appendix C.

5. Backgrounds

Ideal PSF analysis requires the signal above background, corrected for pixel-to-pixel variations in response. The latter is distinct from thermal noise effects and requires accurate flat-field knowledge for the detector as a whole. Since that has not been established at present, the best we can do is subtract off the thermal background noise and bias signal, based upon the no-source background images taken at the beginning and end of each XRCF imaging sequence. These generally consist of a pair of images, at integration times of 1 sec and 60 sec, with the MCP set to operating voltage for that image series, the filter wheel set to the "open" position, and the X-ray source blocked off. Thus the signal present in these images derives from the bias voltage, thermal noise, and any stray visual or X-ray photons or cosmic rays that may have penetrated down through the detector stack.

A smooth, mean background to be subtracted from the point-source images for the PSF analysis was generated from the no-source background images by the following steps:

1) Identify and collect all useful 1-sec and 60-sec no-source background exposures.

It was found necessary to exclude a few images due to a noticeable streaking at low DN levels, probably due to intermittent electronic interference in the test setup. An example of such an image is shown in Fig. 3. A total of 32 1-sec and 59 60-sec images were utilized for this purpose, as listed in Appendix B. All these images were taken in the linear-scaled output mode. A small number of log-scaled images were obtained, but these were too few to be useful in the PSF analysis.

2) Add separately all images at the two integration times to reduce the noise seen in individual images.

This also facilitates identification of persistent and flickering "hot" or "dead" pixels. For this operation the image data are first converted to floats. (The entire analysis is done in floating-point arithmetic.)

The 1-sec and 60-sec summed, mean images are depicted in greyscale in Fig. 4. The most evident characteristics are:

a) the horizontal striping, due to the use of the reference pixel.
b) the "humped" large-scale shape of the background (broad maximum in intensity occurring about 1/3 of the way in from the left of the image.
c) the dark (low DN) region along the lower edge of the 60-sec mean image.

The persistence of the striping through the averaging process reflects small differences in sensitivity among the shielded reference pixels. The hump shape in the background and the dark lower edge both likely derive from thermal effects associated with the test setup. (See discussion in Berthiaume, 1998.)

The same data are shown in pseudo-3D perspective view (height corresponding to DN value) in Fig. 5. In addition to the above effects, the pixel-by-pixel noise is apparent.

3) Eliminate hot pixels and stray hits.

The tallest peaks in Fig. 5 correspond to hot pixels, which must be accounted for in the analysis. In addition, stray hits in the individual background images contribute to the summed, mean images; the few cases where significant, localized DN thus accumulate also need to be eliminated from the final, smoothed backgrounds.

Direct application of de-spiker algorithms (usually based upon local mean or median averaging) to individual background images is complicated by the underlying striping in the SXI CCD. Hence it was decided to clean instead the summed, mean background images, applying the following procedure line-by-line:

a) Compute the average ($\overline{\mathrm{DN}}$) and standard deviation (σ)
b) Identify all points for which $|\mathrm{DN}-\overline{\mathrm{DN}}| > \kappa\sigma$. We set the parameter $\kappa = 3$ throughout this PSF analysis.
c) Replace all such points with the average of the adjacent pixels

4) Smooth the resulting "cleaned" background images.

Although the mean noise level is reduced by the averaging, the residual variations are large enough to preclude application of the raw mean backgrounds to the PSF analysis. Smoothing is therefore required and it is accomplished by line-by-line application of the IDL `SMOOTH` routine using three-point averages, repeated 30 times.

(The ends of each line in the image are not properly treated, but they do not come into play in the PSF analysis.) The resulting smoothed images are written out to disk and are stored for use in the PSF analysis. (See details below).

Improved backgrounds would include the effect of hot pixels, which need to be identified on a sequence-by-sequence basis and to be added back to the smoothed reference backgrounds before being subtracted from the image data. The number and magnitude (a few DN) of hot pixels in the point images is too small to affect the PSF noticeably because of the large number of pixels contributing to each PSF determination.

6. Basics of the PSF Analysis

This section covers those issues common to all the PSF data reduction: background subtraction, centroiding, and the basics of the functional fitting applied to these data.

6.1 Background subtraction.

The stored, smoothed backgrounds for 1-sec and 60-sec images will be referred to as `s1bkgd` and `s60bkgd`, respectively. The appropriate smoothed background shape `sbkgd` for images at a different integration time is obtained by linear interpolation between these two reference backgrounds.

Once `sbkgd` is computed, it remains to scale the reference background shape line-by-line to the individual images. For each image, we first define a square region of interest (ROI) encompassing the image of the point source and then a pair of rectangular background regions of interest (BROI) flanking the ROI. (See Fig. 6.) The ROI is centered upon the pixel with the highest DN, taken as the provisional center of the point-source image. For the on-axis images, the ROI extends ±150 pixels (750 arcsec) in each direction about the nominal center, and the BROIs are each 50 pixels wide.

The additive scaling between `sbkgd` and the BROI data is determined <u>line-by-line</u> in the following steps:

a) Obtain the average DN ($=\overline{\mathrm{DN}}$) and standard deviation (σ) in the BROIs (combining the pixel data in both BROI segments).
b) Discard hot pixels and stray hits in the BROI by retaining only the pixel data for which $|\mathrm{DN}-\overline{\mathrm{DN}}| < \kappa\sigma$.
c) Recompute the $\overline{\mathrm{DN}}$ in the BROIs, using only the cleaned data.
d) Compute the $\overline{\mathrm{DN}}$ in `sbkgd`, for exactly the same data points.
e) Determine the net shift between the smoothed background and the BROIs as $\mathrm{DN}_{\mathrm{shift}} = \overline{\mathrm{DN}}_{BROI} - \overline{\mathrm{DN}}_{sbkdg}$
e) Finally, the corrected DN (=CDN, the DN above background) at any point in the image ROI is computed as $\mathrm{CDN}_{\mathrm{img}} = \mathrm{DN}_{\mathrm{img}} - (\mathtt{sbkgd} + \mathrm{DN}_{\mathrm{shift}})$.

6.2 Centroiding and binning of data.

For each point-image ROI, the location of the centroid of the point-source image is established within a ±10-pixel sub-ROI centered upon the pixel with the peak DN value. Relative to the center of the peak pixel, the centroid is defined as:

$$X_0 = \frac{\sum\limits_i (x_i \, DN_i)}{\sum\limits_i DN_i} \quad ,$$

and similarly for Y_0. The reason for centroiding upon a small region surrounding the core of the image, rather than upon the entire ROI, is that photons scattered just outside the core can occasionally produce enough DN in individual hits to skew the centroiding. This is particularly a problem at higher voltages and shorter (Al) wavelengths. By limiting consideration to the core, more accurate estimation of the true centroid is achieved and the mean half-width of the PSF is reduced by an arcsec or more.

Next, the distance of each pixel in the entire ROI relative to the core center is determined as

$$r_i = \sqrt{(x_i - X_0)^2 + (y_i - Y_0)^2} \quad .$$

The $\overline{\mathrm{DN}}_i$ are collected in bins according to r_i, with the binsize (Δr) being set at 2.5 arcsec. The number of SXI pixels falling within an annulus of radius r and width Δr is roughly $2\pi r \Delta r/(5.0)^2$ per image. For a data set with $\sim$80 images, the number of pixels contributing to the statistics of each bin thus runs from 80 at image center to more than $40,000$ at 500 arcsec.

It is instructive to plot the locations of the centroid of the individual images comprising the data sets. Fig. 7 shows the centroid locations for C on-axis image sets at 699V, 828V, and 873V and the Al on-axis 873V series. Each symbol records the location of the computed centroid within the pixel pattern. Effects prominent in the centroid plots are the tendency to form two or more distinct clumps in some sets, and a general increase in scatter of the centroids at higher voltages and at shorter wavelengths. The discrete clumps appear in those data sets (bottom panels) where half the images were collected on one day (asterisks), half another (diamonds); in the interim, the location of the XRCF source shifted slightly with respect to the CCD pixel pattern. The increase in scatter with voltage comes from the statistics of the MCP [DN/ph, number of photons/image], whereas the increase at short wavelength is due to the wider scattering from the mirror at Al.

The results of the centroiding and binning process are shown in Fig. 8, which depicts the 873V image series data at both Al and C wavelengths. Semi-log (top) and log-log (bottom) displays are included to highlight different aspects of the distributions. The dots represent the binned averages, and the envelope traced out by the solid lines is a measure of the uncertainty in each bin value.

The measure of uncertainty requires some discussion. The standard deviation, σ, in bins for which $r \gtrsim 50$ arcsec is of the order of one, implying very large error bars for most of the PSF. The standard error in the mean, σ_M, for all pixels in each bin of all the images in the entire data set is $\sigma_M = \sigma/\sqrt{N}$, where $N = N_{bin} * N_{images}$, N_{bin} is the number of pixels contributing to a bin in each image, and N_{images} is the number of images composited. As mentioned above, N is tens of 1000s in the wings of the image; error bars computed on this basis would be unrealistic. Hence the uncertainty measure adopted here is the standard error of the bin values over the data set, $\sigma_{bin} = \sigma/\sqrt{N_{images}}$, ie., the standard deviation for each bin divided by the square root of the number of images. This accounts for the statistical impact of summing bin averages over all images. Unless otherwise stated, all error estimates quoted in this analysis make use of σ_{bin}. Finally, we caution that systematic error in the background subtraction, which is spatially varying and of non-negligible magnitude, is not accounted for in the quoted uncertainties (see item 5, below).

It can be seen that the data trace out a relatively smooth and regular distribution out to about 600 arcsec, where a marked drop-off to very low DN values ensues. For the C images, this occurs at about the 0.05 DN level, whereas for Al it is at about 0.10 DN. The nature of this drop-off is a key issue, and will be discussed in greater detail in Section 10.

6.3 Fitting scheme.

The YOHKOH SXT instrument PSF was fit with a Moffit function [Martens, Acton, and Lemen, *Solar Phys.*, **157**, 141, 1995], which is essentially a modified Lorentzian profile. The Moffit function is given as

$$M(r) = \frac{A}{[1 + (r/r_0)^2]^B}$$

where

A = the central peak value

r_0 = the radial scale factor of the core of the profile

B = the power law exponent regulating the wings of the profile

For $r << r_0$, the Moffit function is nearly gaussian, while for $r >> r_0$ it falls off as r^{-2B}. As the SXT data reduction demonstrated, this function mimicks the actual response of the mirror-CCD combination quite well.

The Moffit function, by itself, does not suffice for the PSF profile for SXI. This is best illustrated in the log-log panels of Fig. 8. The inner portion of the Al and C profiles can indeed be readily fit with the Moffit curve out to about 50-70 arcsec, but beyond that point there is an extended power-law falloff, with a much slower decline than r^{-2B}. This feature in the PSF will be referred to as the "halo" and is discussed extensively below. Typically, we find that the decline in the outer part of the Moffit fit is of the order of $r^{-3.2}$, whereas in the extended wings (halo) it is roughly $r^{-1.5}$. It is not clear yet what the source of the extended scatter may be. Extended power-law behavior has been noted in other X-ray optical systems and has been attributed to surface micro-roughness errors (e.g., Saha, Leviton, and Glenn, *Applied Optics*, **35**, 1742, 1996).

The power-law function we fit to the extended wings is

$$P(r) = \frac{P_0}{(1 + r)^D}$$

where

P_0 = the central peak value
D = the power-law exponent

Forcing a simultaneous fit of $M(r)+P(r)$ using standard conjugate-gradient techniques is complicated by the presence of the two power law relations outside the gaussian core of the distribution. Hence we have elected to fit the distribution with a piece-wise continuous splicing of the Moffit and power-law functions. The following procedure gives us some latitude in adjusting the fit to the particular distribution, and it can be semi-automated quite readily. Statistical weighting ($1/\sigma_{bin}^2$, where σ_{bin} is the bin standard deviation) is used during the fitting process.

a) Define an inner domain, $0 < r < R_M$, over which the Moffit function is fit to the core of the profile. The fit is implemented in IDL using the `CURVEFIT` routine, which is based upon the conjugate-gradient technique of Bevington [1969], with statistical weighting applied. R_M is nominally in the range of 60-70 arcsec.

b) Define an outer domain, $R_{P1} < r < R_{P2}$, over which the power-law function is fit, again using `CURVEFIT`. (The two fitting domains need not overlap or abut exactly, so $R_{P1} \neq R_M$, in general). R_{P1} and R_{P2} are selected by visual inspection, with R_{P2} being chosen to coincide with the distance at which the profile is approaching, but not within, the noise. For this analysis, $R_{P1} \sim 70$ arcsec and $R_{P2} \sim 600$ arcsec.

c) Find the break-point between the two fits (i.e., the radius R_{bp} at which the two functional fits are equal). For large r, this point is found with adequate precision to be

$$R_{bp} = \left(\frac{A}{P_0} r_0^{2B}\right)^{[1/(2B-D)]}$$

d) The final fit $F(r)$ is thus

$$F(r) = \begin{Bmatrix} M(r) \\ P(r) \end{Bmatrix} = \begin{cases} 0 < r < R_{bp} \\ R_{bp} < r < R_{P2} \end{cases}$$

and the total DN in an image is given by

$$E_{tot} = 2\pi \int_0^{R_{P2}} rF(r)dr = 2\pi \int_0^{R_{bp}} rMdr + 2\pi \int_{R_{bp}}^{R_{P2}} rPdr \quad .$$

The radius at which half the total energy (including halo) is encircled is

$$r_{E/2} = r_0 \left[\left(\frac{E_\infty}{E_\infty - E_{tot}/2} \right)^{(1/(B-1))} - 1 \right]^{1/2} \quad ,$$

where E_∞ is the energy in the Moffit core out to $r = \infty$.

There is a tacit assumption in all this that the fit to the inner Moffit part of the distribution (in particular, the parameter B defining the Moffit power law domain) is unaffected by whatever is producing the halo. Justification for this approach is provided in Section 9.

Fig. 9 shows the final fit to the 873V Al (top) and C (bottom) on-axis PSF data. Semi-log plots are at left, log-log at right. The legend for each plot contains the following information:

- Data set, date(s) images taken
- X-ray source, MCP voltage, integration time, hardware filter wheel position
- Image position setting (FOV angle: yaw, pitch), in arcmin
- Number of images contributing to PSF
- DN above background in point-source image; total is stated on first line, Moffit and halo contributions on second line in parentheses
- Fit parameters (a=), in sequence: A, r_0, B, P_0, D, with uncertainties, σ_{bin}
- χ^2 of fit, stated for Moffit and halo parts separately
- Region over which fits applied: [$0, R_M$, R_{P1}, R_{P2}] (arcsec)
- R_{bp} (arcsec)

6.4 Encircled energy.

Encircled energies are computed based upon the formulas given in Appendix A. (Many useful relations concerning the Moffit function and the power-law fit are also presented there.) The computation takes into account the piece-wise nature of the fit, with the expression for $M(r)$ being used out to R_{bp} and that for $P(r)$ being used from R_{bp} out to R_{P2}.

The total DN enclosed, and therefore the encircled energy fraction, depends directly upon the assumed R_{P2}. This comes about because for any PSF profile dropping as r^{-2} or slower, the integral of the signal out to infinity is unbounded. As will be documented in Section 10, there appears to be a well-defined cut-off in signal between 600-700 arcsec from image center, and we will use $R_{P2} = 630$ arcsec throughout the analysis.

The encircled energy fractions associated with the 873V Al and C PSFs of Fig. 9 are presented in Fig. 10. The legend for the encircled energy plots also presents the encircled energy percentages for a select range of radii. ("Ensquared" energies, which take into account the pixel geometry and feature in the SXI performance specs, may be approximated by multiplying the quoted EE figures by a factor of $4/\pi$.)

6.5 Systematic Error.

The uncertainties referred to above relate to random, statistical error in the analysis. However, it is important to obtain a feel for the systematic error in the data reduction. In particular, we need to estimate the magnitude of the systematic error in the background subtraction and in the fitting scheme, as imposed by the detector pixelation.

6.5.1 Background subtraction.

Sources of systematic error in the background subtraction include thermal variations from data run to data run, inaccuracy in fitting the mean humped background, and nonlinearity in the rise in background level between `s1bkgd` and `s60bkgd` as a function of time. The magnitude of the systematic error is estimated by assessing how well the linear superposition of `s1bkgd` and `s60bkgd` with respect to image integration time fits the actual backgrounds in the images used in the study. For this test, we record for each image the mean residual DN in the background sampling box, averaged over the lines of the BROI (typically, 301 lines $\times$ 100 pixels per line enter the average). If `sbkgd`, the temporally interpolated smooth background, accurately describes the actual background, we expect that the mean residual DN in each image should tend to zero, since the line-by-line shifts are presumed to be due strictly to random thermal noise in the reference pixels in the CCD.

We examine three different data sets, each contributing a different perspective on the nature of the background error. The results are presented in Fig. 11, where we plot the mean residual DN and the RMS deviation (averaged over the BROI) for each image in a data set as a function of integration time. The top pair of graphs is from the the on-axis Al and C PSF images, the middle pair is from the SLF voltage sensitivity series for Al, Mg, Cu, and C sources, and the bottom pair is from the filter series, also for all four sources. In each plot, the images from a given source are distinguished by the different symbols. The PSF set is most broad-ranging in terms of conditions applying when the images were taken, as the sets were taken on different days at a variety of MCP voltages. Thus the scatter seen as a function of integration time may be affected by test parameters other than integration time alone. The middle and bottom data sets were each taken within a few hours on a given day; thus if we restrict attention to a single source, the day-to-day variations should be eliminated. In addition, the bottom (SLF) data set images were all taken at a fixed MCP voltage, for a given source. Finally, all mean and RMS deviation plots are to the same scale, for intercomparison.

The filter set (bottom) is perhaps simplest to interpret. The Al and C images were taken at 873V, the Cu and Mg at 907V; although the different sets were taken on different days, there is no clear trend with integration time and the magnitude of the deviations is least. The RMS deviation deviates from the anticipated linear relation with integration time, with the short-exposure images showing as low; this behavior is noted in all three sets. The SLF series suggests a trend toward greater mean deviation with increasing integration time, but here both date of test and MCP voltage vary from set to set. Lastly, the PSF series shows perhaps the most pronounced spread in mean deviation, but it is not clear that there is any trend with integration time. All the images at the 50s integration time, for example, are from the 747V C fine scan set (all taken the same day), and in the aggregate they show an offset of about -0.02DN from zero. The C images at 65s integration time, from the 699V on-axis PSF set taken another day, show a similar scatter and offset, but the latter is in the positive direction.

Since the difference in mean DN between `s1bkgd` and `s60bkgd` is $\sim$1 DN, the above offsets correspond to a mean error of $\sim$2% in adjusting for the variation in the humped background shape. For full-well images used in the PSF analysis, an error of a few hundredths of a DN is near the 10^{-5} level in net response. We conclude that whatever the precise nature and sources of the systematic error in subtracting the smooth background, the mean systematic error is too small to seriously affect the results, although minor artifacts may remain.

6.5.2 Pixelation

Systematic error due to pixelation effects are more serious. This error comes about because the actual PSF characterizing the output signal exiting the bottom of the fiber optic taper (FOT, the channels of which, together with the MCP channels and the grains of the phosphor, spatially discretize the output signal) is sampled by the grid of pixels in the CCD. With the SXI pixel size being of the order of the anticipated half-width of the detector stack PSF, significant smearing of the input PSF occurs for pixels near the peak of the point-source image. In particular, determination of the Moffit constants A and r_0 is affected. Far ($r >> r_0$) from the image center the smearing effect is quite small, and the DN in a pixel there approaches the Moffit value evaluated in the middle of the pixel; thus B is much less affected by pixelation effects.

To evaluate the magnitude of this error, we performed several tests. First, to establish that the fitting routine operates correctly, it was demonstrated that fit parameters for a Moffit function evaluated at a set of precise, discrete points r_i are determined to near machine accuracy. Next, to mimick the pixelation effect, a Moffit function typical of the images in the analysis ($A = 1000, r_0 = 7.0, B = 1.4$) was cast onto a 5×5 arcsec pixel pattern, with the value in each pixel being the sum over a set of 1×1 arcsec subpixels (i.e., the value in a pixel is the mean of 25 sub-samples). The synthetic image was reduced by the same routines used in the PSF analysis. This procedure was executed for a point-image whose peak falls exactly in in the center of a pixel, for one falling at the extreme corner where four pixels join together, and for an intermediate case. This test represents the best possible fit that can be obtained by this method, since the input Moffit function is perfectly symmetric and regular, there is no noise, no signal is lost in the channels around each pixel, the background is zero, and each pixel responds identically to a given input.

The results are summarized in Table 1. The first column refers to the variable evaluated, the second to the input (exact) function, the third to the fit for the case where the input Moffit distribution is centered on the center of the pixel, and the last two for cases where the image center is offset from pixel center (x and y offsets in arcsec).

From the table, it can be seen that the pixelation generally serves to smear the image (degrade A and enlarge r_0). Pixelation effects alone contribute a $5 - 10\%$ error in estimates for A and r_0; the error in B is notably less. The σ's returned by the fitting routine are roughly consistent with the actual deviation from the known input values. The greatest uncertainty in A and r_0 is for the case where the image peak is at the corner of the pixel array; in this instance the innermost datum for the fit lies farthest from the actual peak, providing poor constraints on the fit at image center. The encircled energy for $r \gtrsim r_0$ is much less prone to error, however, because of the better statistics. The last two lines show that the systematic error in the image centroid is a few tenths of an arcsec.

Table 1. Fit Parameter Test

	Input Moffit Fcn	Output Moffit Fit (0.0,0.0)	Output Moffit Fit (1.5,1.1)	Output Moffit Fit (2.5,2.5)
A	1000.0	904.4	938.3	933.4
r_0	7.00	7.62	7.30	7.39
B	1.40	1.44	1.41	1.42
σ_A	0.00	86.6	59.2	169.1
σ_{r_0}	0.00	0.57	0.42	0.78
σ_B	0.00	0.051	0.036	0.049
FWHM	11.2	12.0	11.6	11.7
σ_{FWHM}	0.00	1.06	0.78	1.40
Ar_0^2	49000	52513	50002	50975
$\mathtt{DN}_{r=65}$	12816	12708	12780	12832
$\mathtt{DN}_{r=\infty}$	15393	14942	15305	15291
$\mathtt{DN}_{\mathrm{peak}}$	1000	947	834	817
$x_{centroid}$	0.0	0.0	1.36	2.29
$y_{centroid}$	0.0	0.0	1.01	2.29

Near image center, pixelation effects lead to an anti-correlation between the Moffit fit parameters A and r_0. That is, for any series of identical images, different combinations of these two parameters fit the innermost encircled energy distributions equally well, especially in the presence of inevitable random variations in the pattern of photon hits. This can be demonstrated by consideration of Eqn. A2, which gives the EE for the Moffit fit out to some radius r. For $r \sim r_0$, it can readily be shown that EE $\propto Ar_0^2$. The effect is borne out in Fig. 12a, which shows a log-log plot for the 79 images of the C 873V on-axis PSF series. The slope of the dashed line corresponds to an $A \propto r_0^{-2}$ dependence. It can be seen that both parameters fluctuate $\pm$(15-20)% about the ensemble mean. Fig. 12b shows the scatter in Ar_0^2 from image to image. Because of the anti-correlation, the product fluctuates less in value, the variation being $\pm$(10-12)% about the mean. Plots (not shown) of the EE out to larger r likewise display $\sim$10% fluctuation. Thus EE-related measures of the image spread, such as the full-width-half-maximum (FWHM) value or the half-encircled energy radius, are more consistent than either A or r_0 individually and provide a more accurate impression of SXI image performance.

7. Fine-scan Analysis

The fine scan test is intended to establish how strongly the PSF and the total DN collected depend upon just where in the pixel pattern the centroid of the point-source image falls. In that sense, the fine-scan series can be considered an adjunct to the systematic error considerations voiced above. Again, images were taken at a sequence of centroid locations finely separated in the x-direction, whereupon the scan was repeated with the image centroid offset half a pixel in the vertical direction. Fig. 13 shows the track of the image centroids across the pixel pattern.

The data are analyzed by obtaining a PSF fit for each image, as discussed above, and examining scatter plots of the various fit parameters as a function of centroid location, looking for any tell-tale patterns. The far wings are not well characterized because the statistics are poor in single-image analyses, but the Moffit cores can be determined with enough accuracy to make the test useful.

The results are shown in Fig. 14. The six panels display scatter plots of the fit parameters A, r_0, B, and D, as well as the FWHM and total DN for each of the 156 images of the fine-scan series. Values for the two vertical offset locations are distinguished by the asterisk and diamond symbols. In no case is any systematic behavior evident, except for a slight increase in A and total DN toward the higher pixel locations. This trend most likely signifies a slight local variation in CCD sensitivity, not any specific pixelation effect. As anticipated, the scatter in D is most severe, while that in B and the FWHM is least. Hence, there is no evidence for any systematic dependence in the determination of the fit parameters upon the location of the image center within the pixel pattern.

8. Primary PSF Results

This section deals with the analysis of the 873V on-axis and off-axis images at the Al and C wavelengths. Within this section, the halo will simply be taken at face value and fit according to the scheme laid out above. A detailed analysis of halo properties will be conducted in the following section.

For all the on-axis analysis, we assume axial symmetry in the image. That is, we bin in annuli around the image center and take no account of any asymmetries in the angular distribution of flux about the core. Distortions of that sort are taken up in Section 8.2.

As background for interpreting the PSF results, it is useful to consider that each image is composed of 1000s of individual photons. From the detector sensitivity calibration (V. J. Pizzo, "NOAA/SEC SXI-M Instrument Analysis Reports: 1. Detector Sensitivity", 4/10/98; see also Sec 2.4 in Berthiaume, 1998), the integrated photon response of the detector is given by

$$\mathrm{DN/ph} = \mathrm{C}_1\,(\mathrm{MCP}/1000)^{\mathrm{C}_2}$$

where the constants C_1 and C_2 are given by:

$$\mathrm{C}_1 = 30.65 \pm 1.18\,\mathrm{DN/ph}, \quad \mathrm{C}_2 = 14.20 \pm 0.02 \qquad [\mathrm{Al}]$$

$$\mathrm{C}_1 = 46.64 \pm 2.19\,\mathrm{DN/ph}, \quad \mathrm{C}_2 = 14.20 \pm 0.12 \qquad [\mathrm{C}]$$

Based upon these relations and the total DN in the images, the number of photons per image for the 873V on-axis series is about 4000 for Al and about 1700 for C. These figures will vary for the other exposures, depending upon MCP voltage, integration time, and FOV angle, but in all cases a large number of photons are collected. The photon hits are statistically distributed with respect to the amount of DN produced in each event.

8.1 On-axis PSF: 873V Al and C images

The fit parameters for the 873V on-axis Al and C images shown in Fig. 9 are summarized in Table 2.

Table 2. Fit Parameters, 873-Volt On-axis Wavelength Series

src	A(DN/px)	r_0(arcsec)	B	P_0(DN/px)	D	FWHM(arcsec)
Al	920±13	6.43±0.12	1.34±0.01	960±201	1.44±0.04	10.6±0.24
C	1007±9	7.26±0.08	1.65±0.01	108±32	1.24±0.06	10.5±0.15

The full-width-at-half-maximum (FWHM) is presented as a gauge of the core image size and is computed from the Moffit relation as

$$\mathrm{FWHM} = 2r_{1/2} = 2r_0\sqrt{2^{1/B}-1}$$

The FWHM is quite distinct from the half-energy radius, which may be assessed from the encircled energy plots (e.g., Fig. 10) or computed via Eqn. A3. It turns out that while r_0 and B differ somewhat at the two wavelengths, the FWHM is nearly the same. Thus the shapes of the PSF in the innermost core region differ only slightly, with the differences becoming readily apparent only farther off axis.

The PSF in these images represents the convolution of the mirror PSF and the detector PSF. On the basis of component tests conducted previously (K. Russell and J. Chappell, "Spatial Characterization of the SXI Flight Detector," NEARL Report, May 22, 1996), it is known that the FWHM of the mirror PSF is approximately the same at Al and C wavelengths and that the detector PSF is much broader than the mirror PSF in the core of the image; in addition, the detector PSF is not a function of wavelength. Hence the fact that the FWHM are nearly equal at Al and C is consistent with expectations.

The wavelength dependence of the PSF should be most visible in the wings of the distributions, where it indeed appears. The PSF in the near wings ($20 \lesssim r \lesssim 70$ arcsec) follows the Moffit r^{-2B} power-law decline, with the fall-off in Al being shallower than for C and containing somewhat more of the total signal in the image.

In addition to the expected Moffit power-law regime in the near wings we find an extended power-law decline (halo) in the far wings, at large distances from the image axis. The bulk of this flux occurs at very low DN levels, and is very hard to detect in the noise when analyzing individual recalibration images. We will elaborate on the halo properties in Section 9.

8.2 Off-Axis Point Spread Function

The off-axis PSF data were all collected at 873V, at both the Al and C wavelengths (cf. Section 4), and the analysis is conducted similarly to the on-axis study. The one big change is to segregate the data by sectors to map out the angular variation of the PSF. That is, a separate PSF analysis, including binning and fitting, was applied to pixels falling within specific arcs about the image center. Eight sectors were established for this purpose, and they are graphically defined in Fig. 15.

The statistical accuracy in any one sector is reduced (relative to the preceding on-axis analysis) by the square root of the number of sectors. Artifacts due to statistical fluctuations in the images and background subtraction errors are more prominent, but we find that eight sectors (averaging over 45°) does not degrade the confidence levels too severely.

The results of the off-axis analysis are presented in graphical form in Figs. 16 (Al) and 17 (C). In each figure, the columns show the angular variation in r_0, B, D, and $r_{1/2}$ (=FWHM/2), respectively, each to a common scale. In each plot, the solid lines trace out the angular variation in the respective quantities, while the dashed lines give the axisymmetric mean. The uncertainties are depicted by the doubling of the lines (not always visible). From bottom to top, the rows show the results for field angles of 0 (on-axis), -6, -10, -14, and -18 arcmin, respectively.

Out to a field angle of 10 arcmin, there is no conclusive indication of angular distortion, and only a slight swelling of the image is evident. Beyond that point, however, a rapid and asymmetric increase in the size of the image is apparent. The statistical accuracy of D in the lower two panels is severely compromised because the sampling box has to be reduced in size as the point-image nears the edge of the CCD.

Values for the fit parameters, averaged over all eight sectors, are summarized in Tables 3 and 4.

Table 3. Fit Parameters, Al 873V Off-axis Series

Pitch	A(DN/px)	r_0(arcsec)	B	P_0(DN/px)	D	FWHM(arcsec)
0	920±13	6.43±0.12	1.34±0.01	960±201	1.44±0.04	10.6±0.24
-6	862±11	6.83±0.12	1.37±0.02	811±165	1.42±0.04	11.1±0.24
-10	625±11	7.88±0.16	1.40±0.02	1122±253	1.50±0.04	12.6±0.33
-14	398±6	11.1±0.24	1.61±0.03	933±227	1.48±0.05	16.3±0.45
-18	224±4	15.8±0.44	1.82±0.04	673±157	1.43±0.05	21.6±0.81

Table 4. Fit Parameters, C 873V Off-axis Series

Pitch	A(DN/px)	r_0(arcsec)	B	P_0(DN/px)	D	FWHM(arcsec)
0	1007±9	7.26±0.08	1.65±0.01	108±32	1.24±0.06	10.5±0.15
-6	986±8	7.52±0.08	1.66±0.01	77±19	1.16±0.05	10.8±0.14
-10	865±7	8.74±0.09	1.74±0.01	66±15	1.11±0.04	12.3±0.12
-14	685±6	12.3±0.14	1.99±0.02	96±19	1.15±0.04	15.8±0.23
-18	570±5	16.4±0.21	2.28±0.03	99±10	1.12±0.01	19.6±0.33

9. Extended Power Law – Halo

The piecewise-continuous fitting scheme adopted to account for the extended power law region in the PSF analysis is ad-hoc, necessitated by the lack of a physical explanation for the halo feature. In this section, we examine the halo feature in detail, to map out its properties as fully as possible. Once a physical explanation is advanced and a basis for a functional relationship established, it may be possible to improve upon the fitting scheme.

Two lines of evidence establish unequivocally that the halo feature is a real instrumental effect, not a spurious artifact of the PSF analysis. First, in a series of bloomed images taken 980217, the net exposure in the deepest images (64s, 907V) exceeded that in the on-axis PSF series (7s, 873V) by about a factor of 15. This raised the DN level in the far wings enough that their inner portions were about 4-5 DN above background. A faint annulus surrounding the Moffit core may be viewed directly in each of the two images taken at that exposure level, simply by adjusting the grey scale to highlight faint features. A raw summation and average of the two images, with the no background subtraction or any other processing applied, is shown in Fig. 18 (left). It is the smooth, faint appearance of the extended feature in this figure that prompted the designation "halo". Second, to demonstrate that the halo is not an artifact of the XRCF, we have located an image (970203.122501.img, C 910V 40sec) from the SLF tests which shows the same feature, albeit weakly. The raw image, with the grey scale suitably adjusted, is shown in Fig. 18 (right).

A specially processed composite of the two XRCF images is shown in Fig. 19. In this case, the usual smooth background subtraction is applied to each image, and centroiding is done with the 6 central columns of the CCD excised to avoid contamination by blooming. The halo is now clearly above the noise level and is very well defined, as is its sharp drop-off (beyond about 600 to 700 arcsec).

Fig. 19 may be compared with similarly processed composites of the 873V Al images used in the primary PSF analysis. Fig. 20 shows on-axis (left) and -10 arcmin offset (right) composites from the PSF series. The halo is fainter, grainier, and less distinct than in the bloomed image composite because the DN levels are much lower. Nevertheless, Fig. 20 establishes that the feature found in the PSF analysis has the same form and visual appearance as that directly observed in the bloomed image. It also demonstrates that the feature is basically the same at Al wavelengths as at C, and that it shifts with the image pointing offset without any noticeable change.

A PSF analysis of the composite XRCF image, modified to exclude bloomed regions, is shown in Fig. 21 (left). Because the core distribution is truncated by blooming, the Moffit fit parameters and total DN estimates are meaningless. However, the halo fit parameters P_0 (scaled to the deeper exposure) and D compare very well with those obtained in the primary PSF analysis (Fig. 9, bottom). Fig. 21 (right) shows an overlay of the 873V C PSF fit, scaled to account for the deeper exposure, onto the data for the composite XRCF image. This plot confirms the essential validity of the primary PSF study.

To probe further the nature of the halo, we present in Fig. 22 plots of the residual signal left after the Moffit core is subracted from the 873V on-axis Al (left) and C (middle) PSF data and from the bloomed C images (right). In each instance, the Moffit fit to the core data (based on data for $r \leq 65$ arcsec) is indicated by a solid line. To separate core and halo contributions, the Moffit fit is subtracted from each binned datum (circles), leaving the residual halo data (asterisks). (For the bloomed C composite image, we use the adjusted 873V C PSF fit parameters. This scaling does not take into account the weak dependence of r_0 upon MCP voltage discussed in Section 10 nor does it include a slight deviation in the measured detector response from the mean DN/photon fit that occurs above ~850V, so the residual scatter of points in the image core for $r < 60$arcsec is greater than that for the Al and C 873V fits.) The residual halo data have the gross form of a declining power law, with well-defined boundaries at each end; the halo population is distinct (and similar) in both Al and C. The relatively sharp cut-off at the inner edge of the halo supports the legitimacy of fitting the Moffit part of the distribution independently of the halo in the region $r \lesssim 100$ arcsec, as we have done. Power-law fits to the residual halo data in the region $200 \leq r \leq 600$ arcsec are indicated by the solid line segments, and the fit parameters are listed as the last two quantities under "a =" in the plot legends. These fits of course differ from those given in Fig. 9, since those were taken over the wider domain $70 \leq r \leq 600$ arcsec, where Moffit and halo contributions overlap. In particular, the slopes in the residual halo are shallower than those quoted in the primary PSF analysis. The slopes for the two C samples agree well within the uncertainties, and their P_0 parameters scale properly for the relative exposures. The Al slope is somewhat steeper than for C, and the difference is statistically significant. Hence a wavelength dependence appears to exist.

The Al and C properties of the residual halo differ also in fractional power content. We can obtain an estimate of how much of the signal resides in the halo per se by subtracting the Moffit fit integrated to infinity from the total DN given by the piecewise fit. The relevant numbers are given in the legend of Fig. 9, under the "total DN above bkgd" entry: for Al, the halo fraction is $8318/22205 = 0.37$, and for C it is $3360/13679 = 0.25$.

Finally, to provide a visualize impression of the halo itself, we present in Fig. 23 three views of the composite, background-corrected XRCF bloomed image from which the Moffit fit has been subtracted. The leftmost panel, grey-scaled over the range $0 < \mathrm{DN} < 4.0$, shows the extended scatter of individual photon hits which overlap the faint underlying halo; this scatter component is produced by the SXI mirror. The middle panel ($\mathrm{DN} < 1.75$) shows both halo and scatter components, while the right panel ($\mathrm{DN} < 0.4$) emphasizes the diffuse halo and its sharp outer boundary.

We are now in a position to summarize what is known about the halo:

- It is diffuse and does not appear to be composed of scattered X-ray photons; it does not have the grainy, statistical distribution of DN/photon hit anticipated with scattered photon hits. The halo is visible as a diffuse feature in single images, and appears as such in deeply exposed images without any background subtraction.
- It has a well-defined outer cut-off at about 600-700 arcsec radius, and a less well-defined inner cut-off between 50-100 arcsec. There is no substantial difference in these values between Al and C wavelengths.
- The halo does not change character as the point source is moved off the center of

the FOV.

- It has the same general form at all wavelengths, and there is no evidence for voltage dependence in the form. However, the magnitude and slope of the inferred power law does differ in the Al and C PSF data, as does the fractional power (relative to what is in the Moffit fit part of the profile). In this sense, the halo does exhibit wavelength dependence.
- The fraction of the total signal contained in the halo is large enough ($\sim$37% at Al, 25% at C) to affect noticeably effective area, encircled energy, and other measures of system performance.
- The diameter of the halo is nearly as large as the solar disk, so the impact upon operations could be substantial.

Although determination of the source of and physical basis for the halo will be left to subsequent studies, we here comment that the wavelength dependence manifest in some of the halo properties does not automatically point at an origin in the mirror. If the halo comes from some additional scattering process in the detector, the inherent difference in the input PSF profile between Al and C at the top end of the detector may couple with the responsible mechanism to produce an apparent wavelength dependence in halo properties.

10. MCP Voltage and Wavelength Dependencies

10.1 PSF MCP-Voltage Dependence: C images

The MCP voltage series consists of four sets of C images, at 699, 747, 828, and 873 volts. Plots of the PSF data and encircled energy for the first three voltages are presented in Figs. 24-26, and those for 873V in Figs. 9 and 10.

It is seen that at the lowest voltage (699V), the peak DN is roughly half that in the other images, since the XRCF source was too weak to produce full-well central intensities even at the longest possible exposure times below about 730V. The higher noise levels in the wings are also quite evident. There is no discernable drop-off in the signal beyond 600 arcsec, but it may be lost in the noise. The drop-off is better defined at higher voltages, and the scatter about the fit decreases as well.

The fit parameters are summarized in Table 5.

Table 5. Fit Parameters, C On-axis MCP Voltage Series

MCP(V)	A(DN/px)	r_0(arcsec)	B	P_0(DN/px)	D	FWHM(arcsec)
699	600±1.5	5.94±0.03	1.54±0.01	56±22	1.29±0.08	8.96±0.06
747	1154±5	6.20±0.03	1.59±0.01	149±37	1.40±0.05	9.16±0.05
828	1307±20	6.11±0.09	1.53±0.01	56±16	1.09±0.06	9.26±0.16
873	1006±9	7.26±0.08	1.65±0.01	108±31	1.24±0.06	10.5±0.14

There is a weak systematic progression toward larger r_0 at higher voltages, but it is not clear that B, P_0, and D change significantly over this range. Identification of trends may be obscured by inclusion of the 747V data, which were gathered with intentionally shifting centroids. The encircled energy performance, as measured by the FWHM, improves slightly toward lower voltages.

10.2 SLF Voltage Series, All Sources.

A more comprehensive picture of the dependence of the fit parameters on MCP voltage and wavelength can be gleaned from the sensitivity series conducted over the SLF voltage range. Because few images were taken at each setting, halo properties are not well defined and hence we focus upon the variation in the Moffit part of the image profile.

Fig. 27 consists of 6 panels depicting the wavelength dependence of the Moffit pararmeters $\{r_0, B, \mathrm{FWHM}\}$ along the top row, and the MCP voltage dependence of the same parameters along the bottom row. The top row is based upon images taken only at 908V and 840V, to assure better statistics with more deeply exposed images. Both r_0 and B exhibit definite wavelength dependence, but the FWHM varies but little with wavelength. In the bottom row of Fig. 27, r_0 and the FWHM show a clear trend toward larger values with increasing MCP voltage, as is expected from the detector properties. For B, which should be a function mainly of the mirror figure, the trend is much less definite, if real at all.

The dashed line in the lower FWHM plot represents the variation in half-power half-width (FWHM/2) with MCP voltage for the detector alone, as reported by K. Russell and J. Chappell ("Spatial Characterization of the SXI Flight Detector," NEARL Report, May 22, 1996). Although the full-system FWHM trend is consistent with the empirical detector MCP variation, the measured FWHM of the detector (13-17 arcsec over the 700-900V range) is considerably in excess of the full-system FWHM measured in this analysis. Since the FWHM of the entire system cannot be less than that of the worst component, a discrepancy therefore exists between the detector results and these XRCF PSF results. Further analysis of the detector measurements is needed to resolve this issue.

11. SXI Sensitivity (Effective Area)

The PSF analysis has ramifications for estimates of the SXI throughput sensitivity (effective area) study. Both the MIT/LL and MSFC analyses were conducted on individual images using direct counting methods within a small ROI bounding the point-source image: the background was first subtracted off (a reference region outside the point-source region being used for scaling) and then the sum of all the DN in the ROI taken.

The MIT/LL study was undertaken before the existence of the halo was established, and the MSFC study did not explicitly take its presence into account. It is therefore essential to determine how much the halo may affect these results.

We show in Fig. 28 a copy of the XRCF bloomed composite (Fig. 19, left) upon which we have superimposed the 61×61-pixel square counting box utilized by MIT/LL (white lines). The black circle indicates the break-point radius, R_{bp}, separating Moffit and halo fit regions for this C image. As can be seen, the counting box includes all of the Moffit part of the image (including the major part of the scattering domain overlapping the halo), but only a small fraction of the extended halo. Fortunately, since the MIT/LL analysis used for background reference the 20 pixels lying at the far edge of the CCD (in the same rows as the 61×61 counting box), the background subtraction should not be adversely affected. The MSFC study used a 50×50-pixel inner counting box for the signal, and the region between that box and an outer, 100×100 box for the BROI; as noted in that report, neglect of the halo does affect their results.

To assess the magnitude of the missing signal, we offer in Fig. 29 a comparison between total DN in images of the SLF-voltage sensitivity series, as supplied from the direct-counting analysis of Berthiaume (1998), and mean, composited PSF-fit estimates to the same data set from this analysis. The different symbols in the plot indicate the ratio between the direct counting estimate of the mean total DN and the corresponding PSF-based estimate (which includes the full halo) for images taken with the four sources, at several voltages. The Al data cluster significantly lower (~60−70%) as a fraction of the PSF estimate than those for the other sources (~70−80%). These values are emminently consistent with numerical integration of the 873V C and Al primary PSF fits, which suggest 65% of the total DN should fall within the MIT/LL counting box at Al, and 78% at C. There is also no evident variation with MCP voltage (the lower DN values correspond to lower-voltage images).

Hence we conclude that direct-counting and PSF estimates of total DN in the images are in agreement, when counting-box limitations are taken into account. Moreover, this result implies that the MIT/LL estimates of the SXI effective areas should be revised upward, by factors of 1.54 (= 1/.65) at Al and 1.28 (= 1/.78) at C. This moves the Al figure closer (from 0.222 to 0.342cm^2) to the expected value, but a substantial deficit appears nonetheless to remain; the estimate at C stays within the error bars for the anticipated value.

12. Focus Map (Encircled Energy)

Two sets of focus map images were taken during the recalibration tests. We present here the results of the first set obtained 980210, in which four images were taken at each position, including the extreme corners of the CCD. All images were taken at the C wavelength, 828V MCP setting. A PSF analysis identical to that employed for the primary PSF study was used to determine the encircled energy distributions.

Fig. 30 shows two plots depicting measures of the encircled energy across the CCD face. In each case, the full 512×512 pixel array is represented, with a "+" indicating the center and the large dashed circle indicating the size of the solar disk. The diameters of the small circles are proportional to the image diameter containing 25% (top) and 40% of the total energy. Sector analysis was not applied, so the circle sizes refer to the axisymmetric mean about the point-source image center. The sizes of the circles are relatively constant across the image of the Sun, indicating reasonably uniform focus across the main part of the FOV.

The small single square and 4-square symbols at the bottom of the two panels show single pixel and 2×2 pixel patterns to the same scale. SXI encircled energy requirements were stated in terms of these pixel configurations, and it is evident that at both levels of encircled energy the specifications are violated by a wide margin.

13. Filter Set

The SXI filter transmissions were checked relative to the anticipated values by simply taking ratios of total DN in the image between exposures with the filter in the optical path and those taken with no filter (filter wheel position #9). The anticipated transmissions are given in Table 8 of Berthiaume (1998).

The four panels of Fig. 31 show the measured transmissions at all four wavelengths. The measurement is relative and does not depend upon the detector DN/photon, so the Mg and Cu transmissions can be estimated as faithfully as those for Al and C. In each case, the asterisk indicates the ratio obtained from the PSF analysis methods, and the large open circle indicates the anticipated value. In agreement with the Berthiaume (1998) report, all the measured transmissions are within the error bounds, with the main exception being the thin beryllium filter in position #5. (The thick beryllium at Mg, the medium beryllium at Cu, and the thick polyimide filter at C all show significant discrepancies, but the intensities in the point images are very low and the error very large.)

14. Resolution

One of the requirement specifications for the SXI system is that the instrument be able to resolve at the 8.33Å wavelength two point sources separated by 15 arcsec at a field angle of 15 arcmin. Using the PSF results from Section 8.2, we can simulate the intensity profile of two adjacent point sources, as shown in Fig. 32. the dotted lines indicate the profiles of the two adjacent point images, and the solid line shows their sum, normalized to unit peak intensity. At left we use the PSF-fit parameters for the 873V -14 arcmin offset test images, on the right those for the -10 arcmin offset. (Recall, the actual offsets were ~2 arcmin greater than the setting value.) The Rayleigh criterion for resolution is that the intensity in the trough should be 81% of the peak value. At -10 arcmin (actually, -12) offset, the condition is met, but not so at -14 arcmin (actually, -16). Since the focus map (Fig. 30) idicates the image spread increases sharply near 15 arcmin offset (the solar limb), their is some ambiguity as to whether the instrument meets the specification, or, if not, by how much. It should be remarked that Fig. 32 presents an optimistic estimate, since pixelation and other effects would degrade the actual resolution of any individual image.

15. Summary

- We have obtained the data intended in the recalibration test.
- The data appear sufficient to enable generation of useful PSFs for operational purposes.
- The data indicate an extended scattering zone or halo in the far wings of the PSF. The halo was not seen in previous tests, and its origin remains unclear.

- The halo is due most likely to photons scattered in the instrument (ie., it is not a spurious facility problem), and it affects the SXI instrument performance analysis significantly. The effective area estimates in particular have to be amended to include this effect. Most importantly, the effective area (as measured by direct counting methods) at the Al wavelength increases by about 50% to 0.342 cm^2, and the encircled energy performance near the image core is degraded by a similar percentage.
- The implications of the halo for operations is substantial. Observation of coronal hole boundaries will be impaired, and large portions of the image may be heavily fogged during large flares. Some of this may be rectified in post-processing, using the PSF information from this report.

16. Future Topics

Although this study is reasonably comprehensive, not every aspect of system performance has been addressed herein, and many additional questions are likely to come up as well. As specific issues arise, this work will form a basis for more extended analyses.